Simulation of the CMS Prototype Silicon Pixel Sensors and Comparison with Test Beam Measurements

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***Abstract*— In this paper we discuss a detailed simulation of silicon pixel sensors. The simulation implements a model of radiation damage by including two defect levels with opposite charge states and trapping of charge carriers. The simulation was compared with test beam measurements on highly irradiated CMS pixel sensors in terms of charge collection across the sensor thickness. The modeling establishes that a double-peaked electric field generated by the two defect levels is necessary to describe the data and excludes a constant density acceptor defect description.**

I. Introduction

The CMS experiment, currently under construction at the Large Hadron Collider (LHC) at CERN (Geneva, Switzerland), will be equipped with a hybrid pixel detector for tracking and vertexing. It will consist of three layers of pixel sensors (100×150 μm^2 cell size) in the barrel region and two disks in the forward region [1]. The whole system will provide three high resolution space points up to a pseudorapidity[1] of $|\eta| < 2.2$.

The innermost barrel layer is expected to be exposed to a fluence of 3×10^{14} n$_{eq}$/cm^2 per year at full luminosity[2], while the second and third layer will be exposed to 1.4×10^{14} n$_{eq}$/cm^2 and 0.6×10^{14} n$_{eq}$/cm^2 per year, respectively.

In this paper we discuss a detailed simulation of the CMS prototype pixel sensors in which the main effects related to irradiation are modeled by defect levels with opposite charge states in the silicon band gap. The collected charge generated by the simulation is compared with the respective distribution obtained from test beam measurements.

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[1] $\eta = -\ln(\tan(\theta/2))$ where θ is the track angle relative to the beam axis.

[2] All particle fluences are normalized to the non-ionizing energy loss (NIEL) of 1 MeV neutrons (n$_{eq}$/cm^2).

II. Prototype silicon pixel sensors

The CMS pixels sensors are manufactured in the "n-in-n" technique, consisting of n^+ structures on n bulk silicon. This allows a partially depleted operation of highly irradiated sensors after space charge sign inversion (SCSI) of the substrate but requires inter-pixel isolation. Two isolation techniques were considered in our latest prototype designs: p-spray, where a uniform medium dose of p-impurities covers the whole structured surface, and p-stop, where higher dose rings individually surround the n^+-implants. Results on the Lorentz angle and charge collection efficiency measurements as well as a detailed description of both designs can be found elsewhere [2], [3]. In this paper we discuss only measurements performed on p-spray sensors.

All our test devices had 22×32 pixels, with a sensitive area of 2.75×4 mm^2 and a thickness of 285$\pm$15 μm. The pixel size was 125×125 μm^2 and oxygen enriched silicon was used to improve the performance after irradiation. After the deposition of the under-bump metalization and the indium bumps, the sensors were cut out of the wafers. Some of them were irradiated at the CERN PS with 21 GeV protons. The irradiation was performed without cooling and bias. The applied fluences were 3, 8 and 11×10^{14} n$_{eq}$/cm^2. In order to avoid reverse annealing the sensors were stored at -20 °C after irradiation and kept at room temperature only for transport and bump bonding. Several sensors were bump bonded to readout chips of the type PSI30/AC30 [4] which allows a non zero-suppressed analog readout of all 704 pixel cells.

III. Experimental setup

The measurements were performed in the H2 line of the CERN SPS in June and September 2003 using 150-225 GeV pions. A silicon reference telescope [5] was used to achieve a precise determination of the particle hit position in the pixel detector. Both the telescope modules and the pixel front-end were mounted onto a common frame. The beam telescope consists of four modules each containing two 300 μm thick single sided silicon detectors with a strip pitch of 25 μm and readout pitch of 50 μm. The resulting intrinsic resolution of the beam telescope is about 1 μm.

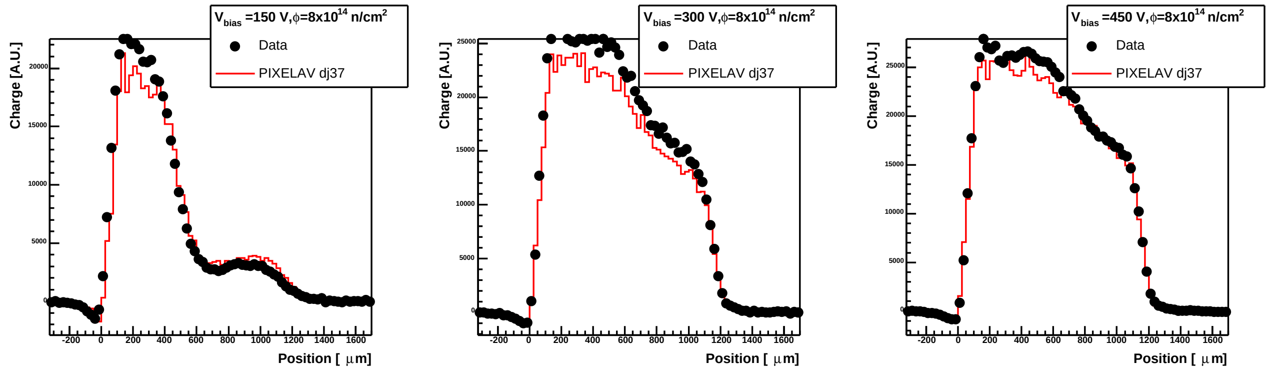

Fig. 1. Average collected charge from particle crossing at a shallow angle of 15° (full dots) compared with the PIXELAV simulation (full line). The measured and simulated distributions are shown for an applied bias voltage of 150 V (left), 300 V (center) and 450 V (right). The pixel sensors are irradiated to a particle fluence of 8×10^{14} n_{eq}/cm^2 and all measurements are taken at -10° C.

The pixel sensor with the bump-bonded front-end chip was mounted on a rotating support positioned between the second and third module. A trigger signal was generated by a silicon PIN diode. The analog signals were digitized in a VME based readout system by two CAEN (V550) and one custom built FADCs. The whole setup was placed in a open 3 T Helmholtz magnet with magnetic field parallel to the beam. The temperature of the test sensors was controlled with a Peltier cooler which was capable of operating down to -30° C.

IV. Pixel Sensors Simulation

A detailed simulation of the pixel sensor was used to interpret the test beam data [7]. The simulation, PIXELAV, incorporates a detailed charge deposition model based upon calculated pion-atomic electron cross sections. The model naturally incorporates energetic delta rays and generates electron-hole pairs with a linear density based upon an empirical differential charge loss distribution. Electron and hole transport is simulated by integrating the equation for the fully-saturated drift velocity of the carriers in electric and magnetic fields. The intra-pixel electric field is taken from a three dimensional field map generated using ISE TCAD software [8]. The integration procedure also includes diffusion and carrier trapping. Induced signal from trapped carriers is estimated using a segmented parallel capacitor model. A final step simulates the electronic noise, the analog response of the readout chip, and the effect of ADC digitization.

V. Results and Conclusions

The measurement of charge collection as a function of the sensor depth was performed using the grazing angle method [6] without magnetic field. The particle beam hits the pixel surface at a shallow angle of 15°. The average charge cluster profiles in irradiated p-spray sensors are shown in Fig. 1 as a function of the distance from the predicted impact position and for different values of the bias voltage. The left part of each distribution corresponds to the n^+ side of the sensor, while the right part corresponds to the region closer to the p^+ backplane. The lower collected charge close to the backplane is a combined effect of a lower electric field and trapping of charge carriers. The measured distributions are compared with the PIXELAV simulation. The TCAD electric field calculation for the heavily irradiated sensors was done in several ways. Initially, it was assumed that the intra-pixel electric field could be described by a constant density of fully ionized acceptor defects across the sensor thickness. When the resulting simulated data were compared with the measured data, the agreement was unsatisfactory. Next a two-defect double junction model [9] was implemented in TCAD. The double-peaked electric field generated by this mechanism has the qualitative features needed to describe the data, but still did not lead to good agreement with the measured charge collection profiles. After an extremely tedious tuning procedure, a range of model parameters that produced good agreement with the data was identified. The resulting simulated charge collection profile is shown as the red histogram in Fig. 1. The modeling establishes that a double-peaked electric field is necessary to describe the data and excludes a constant density acceptor defect description. The allowed model parameter range can accommodate the expected leakage current (which is smaller than the observed current) and the observed signal trapping rate needed to describe the data.

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